

RR Lyrae stars in the *Gaia* era

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Abstract. *Gaia*, the European Space Agency spacecraft successfully launched on 19 December 2013, entered into nominal science operations on 18 July 2014 after a few months of commissioning, and has been scanning the sky to a faint limit of $G = 20.7$ mag since then. *Gaia* is expected to observe more than a hundred thousand RR Lyrae stars in the Galactic halo and bulge (most of which will be new discoveries), and to provide parallax measurements with about $10 \mu\text{as}$ uncertainty for those brighter than $\langle V \rangle \sim 12\text{--}13$ mag.

Status and activities of the spacecraft since launch are briefly reviewed with emphasis on preliminary results obtained for RR Lyrae stars observed in the Large Magellanic Cloud during the first 28 days of science operations spent in Ecliptic Pole scanning mode and in light of the first *Gaia* data release which is scheduled for summer 2016.

1. Introduction

Gaia is the ESA cornerstone astrometry mission building on the heritage of *Hipparcos* (Perryman 2009). It is an unbiased all-sky ($\sim 40,000 \text{ deg}^2$) survey that will enable science with one billion sources by providing μas accuracy astrometry (parallaxes, positions and proper motions) and milli-mag optical spectrophotometry (luminosities and astrophysical parameters) for sources down to a limiting magnitude $G^1 = 20.7$ mag, as well as spectroscopy (radial velocities and chemistry) for objects brighter than $G = 15.3\text{--}16.2$ mag (and $G > 2$ mag).

Key-science topics that *Gaia* will address range from: the study of the Milky Way (MW) structure and dynamics to the Galaxy star formation history (e.g. Cignoni et al. 2006, for a similar study based on *Hipparcos* data), stellar astrophysics to binaries and multiple stars, brown dwarfs and planetary systems to solar system objects, galaxies to quasars and the reference frame, and fundamental physics to general relativity.

The backbones of *Gaia*'s science are also i) the discovery of thousands new variable sources thanks to repeatedly monitoring the whole celestial sphere and, most importantly, ii) the absolute calibration of fundamental standard candles of the cosmic distance ladder such as hundreds/thousands of RR Lyrae stars and Cepheids that will have their parallax (hence distance) measured by *Gaia* at $\sim 10 \mu\text{as}$ accuracy.

¹ G denotes *Gaia* broad-band white-light magnitude.

A better knowledge of the cosmic distance ladder has a profound impact in areas ranging from stellar astrophysics to the cosmological model. With the successful launch of *Gaia* and the release of first astrometric data scheduled for mid-2016, this topic has now become extremely hot and timely.

2. *Gaia*'s payload and instruments

Gaia scans the sky from a Lissajous-type orbit around the L2 Lagrangian point of the Sun and Earth-Moon system, where the spacecraft will remain for its 5-year nominal lifetime and possibly for an additional year, if the mission is extended. The spacecraft features two primary mirrors mounted on a silicon carbide toroidal optical bench, each with $1.7^\circ \times 0.6^\circ$ field of view (FoV). The two mirrors are separated by a basic angle of 106.5° and share a combined focal plane where there are 106 assembled CCDs devoted to different functions: 2 wave-front sensor and 2 basic-angle monitor CCDs; 14 Sky Mapper CCDs with task of detecting sources entering into *Gaia*'s two fields of view; 62 astrometric field CCDs devoted to astrometric measurements and providing integrated white-light (*G*-band) photometry over the wavelength range: 330-1,050 nm; 7 Blue and 7 Red Photometer (BP and RP) CCDs providing low resolution ($R \sim 20$ -90) spectrophotometry for each source over the wavelength ranges 320-660 and 650-1,000 nm, respectively; and 12 CCDs for the Radial Velocity Spectrograph (RVS) obtaining $R = 11\,500$ spectra in the Ca triplet (845-872 nm) region for sources brighter than $G \sim 15.3$ -16.2 mag (and $G > 2$ mag). A more detailed description of *Gaia*'s payload, instruments and focal plane can be found in Prusti (2012) and at <http://www.cosmos.esa.int/web/Gaia/spacecraft-instruments>.

The way *Gaia* scans the sky is due to the spacecraft spinning in 6 hours around its axis, which points in a direction 45° away from the Sun, and to the spin axis precessing slowly on the sky (precession period of 63 days and 29 revolutions around solar direction in 5 years). As a result of the precession, the sky seen by the two fields of view every 6 hours changes slowly with time, allowing repeated full sky coverage over the mission lifetime. At the same time, due to the 106.5° separation between the two fields of view, objects transiting FoV₁ at time t_0 will then transit FoV₂ at $t = t_0 + 106.5$ minutes. This will then repeat 6 hours later and then again 10-30 days later. These figures give rise to an optimum nominal scanning law by which over the 5 years *Gaia* will observe each source from 10 to 250 times (the actual number depending on sky position, with maximum frequency at $|\beta| = 45 \pm 10^\circ$) and on average about 70 times in photometry and about 40 times with the RVS. The sky coverage of *Gaia* after 5 years is shown in Fig. 4 of Prusti (2012). Further details on *Gaia*'s scanning law can be found at <http://www.cosmos.esa.int/web/Gaia/scanning-law>. The scanning law determines the typical cadence of *Gaia* multi-epoch observations and, in turn, bears on the alias patterns we may expect to show up in the power spectrum of *Gaia* time-series data.

Gaia does not send images down to ground. Figure 1 shows a star density map of the sky observed by the spacecraft produced by visualizing the number of stars between $G = 13$ and 18 mag detected per second by *Gaia*'s fields of view. These stars represent only a very small fraction of all detected stars and are used by the attitude control system of *Gaia* to ensure the spacecraft's orientation is

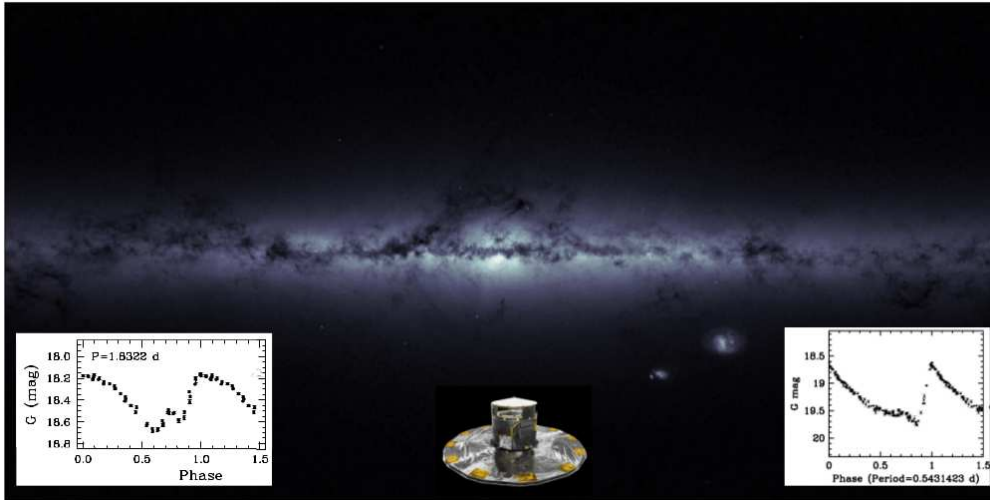


Figure 1. Star density map of the sky produced with *Gaia*'s house-keeping data (Credits: E. Serpell, ESA/Gaia-CC BY-SA 3.0 IGO) showing our Galaxy and the two Magellanic Clouds. The two insets show *Gaia* G-band light curves for a Cepheid on the left (from http://www.cosmos.esa.int/web/Gaia/iow_20150528) and an RR Lyrae star on the right (from http://www.cosmos.esa.int/web/Gaia/iow_20150305) observed by *Gaia* in the Large Magellanic Cloud (LMC) during the first 28 days of science operations in Ecliptic Pole Scanning Law (EPSL).

maintained with the desired precision. The Milky Way and the two Magellanic Clouds are easily recognized.

3. Current status and post-launch performances

After a few months of commissioning, *Gaia* entered into nominal science operations on July 18, 2014. The routine phase started with 28 days in EPSL, after which the spacecraft went into Nominal Scanning Law (NSL). *Gaia*'s EPSL footprint around the South Ecliptic Pole (SEP) intercepts a portion of the LMC containing a large number of RR Lyrae and Cepheids which were monitored repeatedly during these first days of science operations. Examples of light curves for an RR Lyrae and a Cepheid observed by *Gaia* in the LMC during the EPSL are shown in the two insets of Fig. 1.

Gaia data processing is handled by the Data Processing and Analysis Consortium (DPAC), an ensemble of approximately 450 scientists and software developers from 20 different (primarily European) countries, organized in 6 Data Processing Centers and 9 scientific Coordination Units, each having its own specific tasks. DPAC processing takes place in a cyclic way and with continuous interaction and exchange among different CUs and *Gaia*'s Main Data Base which resides at the European Space Astronomy Centre (ESAC) (see <http://www.cosmos.esa.int/web/Gaia/data-processing>). Processing of the variable sources observed by *Gaia* is the task of Coordination Unit 7 (CU7) whose main Data Processing Center is at ISDC in Geneva.

Gaia is now fully operational, scanning the sky to a faint limit of $G = 20.7$ mag (and completeness at $G = 20$ mag) since the start of science operations and on average collecting data for 50 million stars per day. For comparison, faint limit and completeness of *Gaia*'s predecessor, *Hipparcos*, are 12 and 7.3-9.0 mag, respectively. Over the first year of operations *Gaia* has collected more than 272 billion astrometric measurements, 54.4 billion *BP*, *RP* photometric measurements and 5.4 billion RVS spectra (see http://www.esa.int/Our_Activities/Space_Science/Gaia/Gaia_s_first_year_of_scientific_observations). Current magnitude limits are: $2 < G < 20.7$ mag for photometry and astrometry, and $2 < G \leq 15.3$ -16.2 mag for the RVS. Stars brighter than $G = 3$ mag are imaged by the Sky Mapper CCDs (Prusti 2014). DPAC has started the cyclic processing and first tests were made on the EPSL dataset.

Post-launch performances have been derived after conclusion of *Gaia* commissioning and standard errors of the end-of-mission *Gaia* photometry, astrometry and spectroscopy have been re-assessed. Tables and plots showing *Gaia* post-commissioning performances can be found at <http://www.cosmos.esa.int/web/Gaia/science-performance>.

4. *Gaia*'s RR Lyrae stars

Eyer & Cuypers (2000) predict *Gaia* to observe about 70,000 RR Lyrae stars in the Galactic halo (based on estimates of the RR Lyrae density in the MW halo by Suntzeff et al. 1991) and an additional 15,000-40,000 RR Lyrae in the MW bulge (based on MACHO and OGLE detection rates available at the time). However, these might be underestimates, as current ongoing surveys such as OGLE, LINEAR, CATALINA, PanSTARRS, PTF, are constantly reporting new discoveries and increased RR Lyrae densities. In conclusion, likely *Gaia* will significantly revise upward the census of Galactic RR Lyrae stars both in the MW and in some of its close companions. Over a hundred thousand Galactic RR Lyrae are expected to be observed by *Gaia*, but compared to *Hipparcos*, only 186 such variables were observed, of which only RR Lyrae itself has an accurate enough parallax ($\sigma_\pi/\pi \sim 18\%$). End-of-mission, astrometric standard errors, in units of μas , for position, parallax, and proper motion, as a function of *Gaia* G magnitude, for a G2V star with $(V - I)_0 = 0.75$ mag and $(V - G)_0 = 0.16$ mag, are summarized in Table 1 of de Bruijne et al. (2014). According to these estimates all RR Lyrae brighter than $\langle V \rangle = 12$ -13 mag will have their parallax measured by *Gaia* to $\sim 10 \mu\text{as}$, whereas individual accuracies will range between 17 to 140 μas for RR Lyrae stars in Galactic globular clusters with horizontal branch luminosity between $V \sim 14$ and 18 mag.

Processing of the variable sources observed by *Gaia* is handled by CU7, that analyzes the calibrated G , BP and RP photometry produced by CU5 to identify variable sources. The CU7 processing chain comprises a number of different modules and work-packages that perform the variability detection, characterize and classify the sources found to vary, and finally produce period, amplitude, mean magnitude, modeled light curves, and stellar parameters that fully typify the confirmed variables. A specific work-package of the CU7 chain is dedicated to the RR Lyrae stars (and the Cepheids) and outputs final attributes for these variable stars, including classification in types according to the pulsation mode

and detection of double-mode pulsation and/or other secondary periodicities. In spring 2015 the CU7 pipeline was tested on data collected by *Gaia* during 28 days of EPSL and 3 days of NSL. About 70 million sources were received from CU5 and processed by CU7. Over twelve hundred RR Lyrae stars were identified, about half of them are new discoveries. Figure 2 shows examples of the *G*-band light curve for RR Lyrae stars in the LMC observed by *Gaia* during EPSL. *Gaia*'s light curves are folded using periods taken from the OGLE IV catalogue of variable stars in the *Gaia* SEP (Soszynski et al. 2012). OGLE *I*-band light curves for these stars are also shown for comparison. This figure nicely showcases the excellent quality of *Gaia*'s photometry (median uncertainties of the measurements are around 0.02 mag) at the faint magnitudes of the LMC RR Lyrae stars (typical average apparent magnitudes are $\langle V \rangle \sim 19.5$ mag) and after a first data reduction by CU5 and a first analysis by CU7.

Gaia data have no proprietary rights – they will become public as soon as they have been fully processed and properly validated. Publication of *Gaia*'s final catalogue is currently planned for 2022, however, there will be a number of intermediate data releases, of which the first one is foreseen in 2016. This first release will contain positions and *G*-band photometry for all-sky single stars, *G*-band time-series photometry and characterization by CU7 of the RR Lyrae and Cepheids observed during the EPSL, and parallaxes and proper motions for about 2 million stars in common between *Gaia* and the Tycho-2 catalogue based on the Tycho-Gaia Astrometric Solution (TGAS; see Michalik et al. 2015 and http://www.cosmos.esa.int/web/Gaia/iow_20150115 for details).

4.1. Science with *Gaia*'s RR Lyrae stars

Thanks to multi-epoch monitoring of the whole celestial sphere, *Gaia* will discover and measure positions and proper motions of thousands of RR Lyrae stars in the MW and its surroundings down to the spacecraft limiting magnitude and will simultaneously determine chemical and dynamical properties for those within reach of the RVS ($G \lesssim 16$ mag). These RR Lyrae will trace the ancient ($t > 10$ Gyr) stellar component all the way through from the Galactic bulge, to the disk, to the halo and have the potential to unveil streams, faint satellites, stellar overdensities, and remnants left over by past interactions and accretions of the MW assembling process. As an example of *Gaia*'s potential in this area, Table 1 summarizes the estimated number of transits per year at the position of classical and ultra-faint Local Group galaxies with RR Lyrae stars within *Gaia*'s reach.

Gaia's complete census of the Galactic RR Lyrae will definitely increase our understanding of the MW structure and formation. However, even more dramatic is the impact *Gaia* will have on the RR Lyrae (and Cepheid) foundations of the cosmic distance ladder. Both the optical luminosity-metallicity ($M_V - [\text{Fe}/\text{H}]$) relation and the near/mid-infrared period-luminosity (*PLZ*) relation of RR Lyrae as well as the period-luminosity and period-Wesenheit relations of Cepheids need an accurate determination of their zero points in order to reliably calibrate secondary distance indicators, and be able to probe cosmologically relevant distances ($D \geq 100$ Mpc). At present, an accurate parallax is available only for a handful RR Lyrae stars. *Hipparcos* measured the parallax for more than a hundred RR Lyrae in the solar neighborhood, but errors are larger than

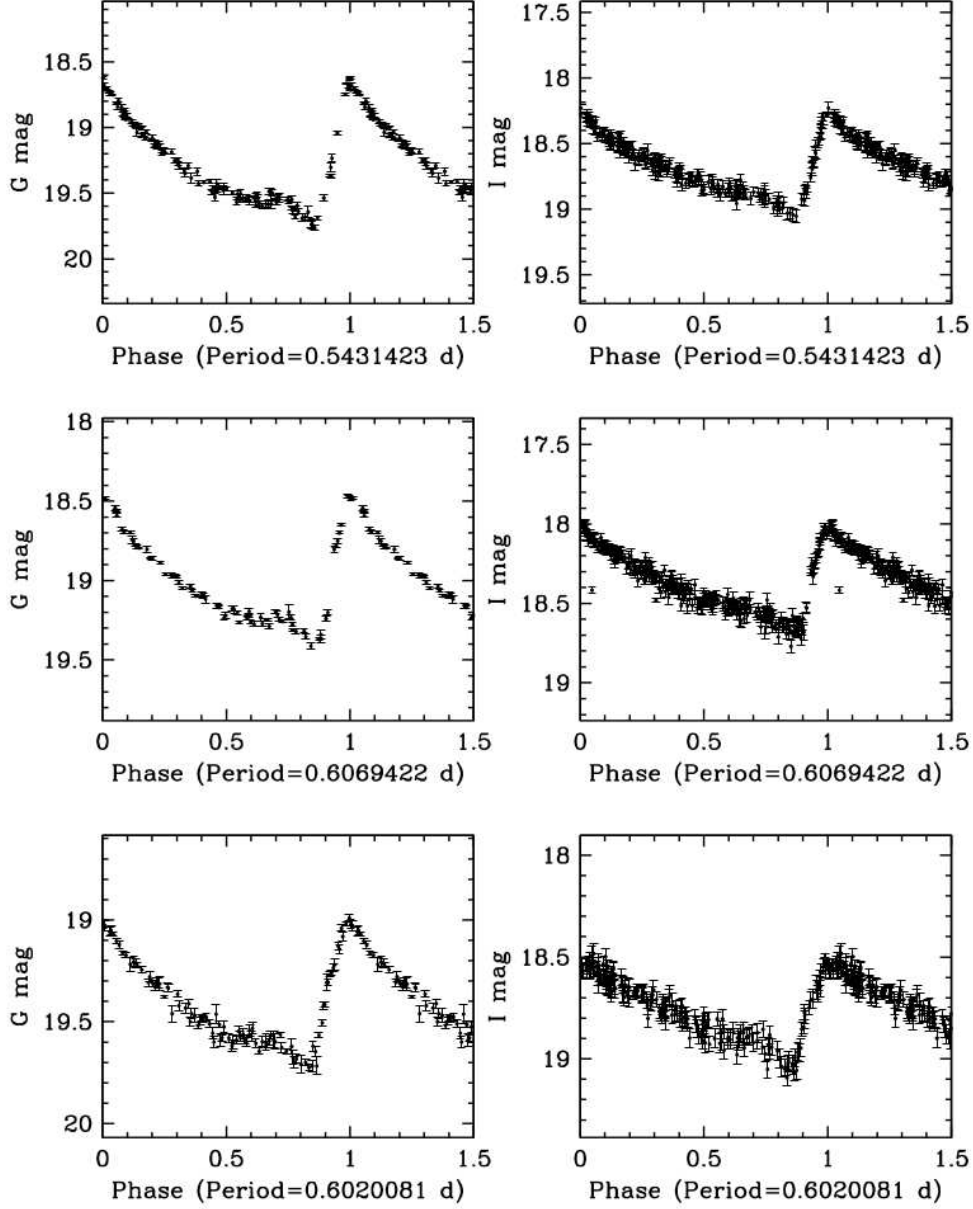


Figure 2. Left panels: *G*-band light curves of fundamental-mode RR Lyrae stars in the LMC observed by *Gaia* during the 28 days of EPSL. Right panels: *I*-band light curves obtained for the same stars by the OGLE IV survey. From http://www.cosmos.esa.int/web/Gaia/iow_20150305.

Table 1. Estimated number of *Gaia*’s transits per year at the position of known close by Local Group galaxies

Name	RA (deg)	Dec (deg)	D ^a (kpc)	1	2 ^b	3 ^b	4 ^b	5 ^b
MW center	266.41	−29.0	—	10	18	34	47	54
Canis Major	108.14	−27.66	7	22	49	72	98	121
Segue 1	51.76	16.081	23	10	20	29	50	59
Sagittarius dSph	283.83	−30.54	26	11	20	32	44	58
Ursa Major II	132.88	63.13	32	19	51	73	138	160
Segue 2	38.416	20.175	35	9	17	26	43	53
Willman 1	162.33	51.058	38	26	53	74	85	97
Bootes II	209.5	12.85	42	10	30	56	77	84
Coma Berenices	186.74	23.403	44	15	33	42	49	61
Bootes III	209.3	26.8	47	15	34	85	107	114
LMC ^c	80.893	−69.75	51	14	28	47	63	81
SMC	13.186	−72.82	64	20	39	54	73	87
Bootes I	210.02	14.5	66	8	23	49	68	77
Draco	260.05	57.915	76	18	36	50	66	84
Ursa Minor	227.28	67.222	76	18	33	46	64	78
Sculptor	15.0375	−33.709	86	21	35	48	65	120
Sextans	153.26	−1.614	86	11	20	27	58	66

^a Distances are from McConnachie (2012)^b Cumulative numbers^c Estimates for the LMC do not include the EPSL transits.

30%. Only for RR Lyr itself ($\langle V \rangle \sim 7.8$ mag) is the *Hipparcos* error in the parallax smaller than $\sim 18\%$. At present, the zero points of the RR Lyrae relations are anchored on only 5 Galactic RR Lyrae with *HST* parallax measured by Benedict et al. (2011). However, *Hipparcos* parallax of RR Lyr ($\pi_H = 3.46 \pm 0.64$ mas, van Leeuwen 2007) differs from the *HST* parallax ($\pi_{HST} = 3.77 \pm 0.13$ mas, Benedict et al. 2011) by an amount corresponding to a 10% difference in distance, although the two values are not totally inconsistent given the large error of *Hipparcos* estimate. On the other hand, use of Benedict et al. (2011)’s parallaxes is not without concern (see, e.g., Section 3.2.2 in Muraveva et al. 2015). *Gaia* will provide individual distances from parallaxes measured to $\sim 10 \mu\text{as}$ for all RR Lyrae brighter than $V \sim 12$ mag (see Table 1 in de Bruijne et al. 2014) and RVS metallicity for those brighter than $V \lesssim 16$ mag. Hence, in a few years from now $\sim 10 \mu\text{as}$ accuracy parallaxes will become available for 100-150 Galactic RR Lyrae spanning a large enough metallicity range to measure both the zero point and slope of the $M_V - [\text{Fe}/\text{H}]$ and PLZ relations directly from these parallax-calibrated sources. Accuracies quoted in de Bruijne et al. (2014) are end-of-mission estimates. However, parallaxes with sub-milliarcsecond accuracy for RR Lyrae brighter than $\langle V \rangle \sim 12$ mag may already be included in the TGAS catalogue published with *Gaia*’s first data release in 2016.

In summary, the unprecedented precision and accuracy of *Gaia* parallax for the local RR Lyrae (and Cepheids) will allow (i) the absolute calibration via parallaxes of these “primary” standard candles, (ii) a test of the metallicity effects through simultaneous abundance measurements, (iii) a re-calibration of the “secondary” distance indicators and (iv) to set up a homogeneous distance lad-

der in and beyond the Local Group, and finally producing a total re-assessment of the whole cosmic distance ladder. This will in turn significantly improve our knowledge of the Hubble constant (H_0). Furthermore, by combining *Gaia*'s photometry, parallax, metallicity and radial velocity information it will be possible to better constrain the physical parameters of RR Lyrae stars, test the pulsation models and their input physics, better determine, for instance, the p -factor used to convert radial to pulsation velocity in Baade-Wesselink studies, better understand double-mode pulsation and the Blazhko effect and many more other phenomena occurring in RR Lyrae stars. This will further improve their use as standard candles and stellar population tracers.

Finally, synergy between *Gaia* and past, ongoing and future surveys covering the full wavelength range from near-UV to the mid-IR, such as OGLE, EROS, LINEAR, CATALINA, PTF, ASAS, PanSTARRS, LSST, 2MASS, VVV, VMC from the ground, and CRRP, SMHASH, CCHPII from space, along with use of upcoming multiplex facilities such as WEAVE, MOONS, 4MOST to complement the RVS spectroscopy, will allow a further quantum leap in the science achievable with RR Lyrae stars in the *Gaia* era.

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